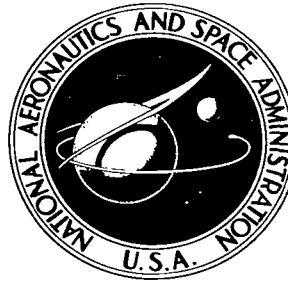


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THE EFFECT OF SIMULATED ABLATION-GAS INJECTION ON THE SHOCK LAYER OF BLUNT BODIES AT MACH NUMBERS OF 3 AND 5

by George E. Kaattari
Ames Research Center
Moffett Field, Calif.



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The effect of simulated ablation of gases on the bow shock layer of spherical-segment-face and flat-face models was investigated experimentally. Ablation was simulated by injecting the gases air, helium, and Freon through the porous front faces of these models into an oncoming air stream for which the free-stream Mach numbers were 3 and 5. Shadowgraph pictures taken during the test usually showed the presence of an interface separating the injected gas and the oncoming air stream. In most cases the bow shock standoff distance increased linearly with the ratio of injected-gas to free-stream mass flow. However, in some cases, large, unstable fluctuations in bow shock standoff distances occurred at large mass-flow ratios. Except when the flow was unstable, the test results at a given Mach number for the different gases correlated with the flow rate of the gas divided by the square root of its molecular weight. The effect of Mach number could be accounted for by including in the correlation parameter the square root of the normal-shock density ratio. The experimental bow shock standoff distances for the spherical-segment-face models were found to be in fair accord with theoretical results. A similar comparison for the flat-face model was not made because of the lack of theoretical results.

INTRODUCTION

Vehicles entering the atmosphere at high speeds are enveloped by high-temperature shock layers. If the temperature is sufficiently high, certain surface materials may be ablated from the vehicle in the form of gas. This ablating gas can have significant effects on the shock layer. Since the shock layer influences the heating and aerodynamic characteristics of the vehicle, it is desirable to define quantitatively the effect of ablation on the structure of the gas envelope.

It is the purpose of this report to present the results of an experimental investigation of the effect of simulated ablation on the subsonic portion of the shock layer of blunt models. Tests were conducted on both spherical-segment-face and flat-face models. Ablation was simulated by injecting the gases air, helium, and Freon at controlled rates through the porous front faces of the models. Some earlier work on spherical-segment-face models (ref. 1) is also discussed.

NOTATION

A	model frontal area, $\pi d^2/4$
a	speed of sound
c	Venturi meter constant
d	model diameter
k	molecular weight ratio of injected gas with respect to air
M_∞	tunnel Mach number
p	pressure
r	model radius, $d/2$
T	temperature
V	velocity
γ	specific heat ratio
Δ	center-line shock-layer thickness
Δ_0	center-line shock-layer thickness at zero blowing rate
Δp	differential pressure
ρ	gas density
$\overline{\rho V}$	average injection mass-flow rate from model

Subscripts

m	condition in Venturi meter
t	tunnel total condition
∞	tunnel free-stream condition
2	behind normal shock

MODELS AND TESTS

Four models were used (fig. 1) each consisting of a cylindrical body with a blunt, porous front face. Three of the models (models 1(a), 1(b), and 1(c)) had identical spherical-segment faces, but different internal geometry. The fourth model (model 2) had a flat face. Different internal designs were used for models 1(a), 1(b), and 1(c) in order to determine whether the resulting internal flow differences would affect the flow in the shock layer. The interior of models 1(a) and 1(b) consisted of a simple conical nozzle. In addition, model 1(a) was provided with four small tubes for measuring pressure, two terminating inside the model and the other two terminating at the porous face. Model 1(c) had an internal calming screen between the conical nozzle and the porous face. The interior of model 2 was identical to that of model 1(c).

The models were tested by injecting various gases through the porous faces into an oncoming air stream. Shadowgraph pictures were taken of the resulting flow. The tests were conducted at the Ames Research Center in the 1- by 3-foot wind tunnel. Total pressures in the wind tunnel ranged from 5 to 40 psia, and the Mach numbers of the free stream were 3 and 5. For the tests at a Mach number of 3, air was injected through the models into the oncoming air stream; for a Mach number of 5, air, helium, and Freon were injected to study the effect of the molecular weight of the injected gas on the bow shock wave. The blowing rate was controlled by means of a needle valve and was metered with a Venturi installed in the gas supply line. The blowing rate, relative to the free-stream rate, was varied by adjusting both the injection rate and the tunnel total pressure. The formulas used to compute the flow rates of the injected gas and of the tunnel air stream are given in the appendix of this report.

RESULTS AND DISCUSSION

The experimental data consisted primarily of shadowgraphs of the models and bow shock waves for different gases and ratios of injected-gas flow rate to free-stream flow rate. Typical photographs are presented in figures 2 through 5. Except for figure 5, the photographs are arranged in columns for the same normalized blowing-rate ratio $\sqrt{1/k} (\rho V / \rho_{\infty} V_{\infty})$. This form of the blowing-rate ratio was adapted from the theoretical considerations of references 1 and 2.

Limited, preliminary pressure measurements by means of the tubes installed in model 1(a) showed little effect of low blowing rates on the surface pressures of this model. At high blowing rates, the measurements made in this manner were not felt to reflect surface pressures accurately under conditions of actual ablation. The pressure data, therefore, were not considered relevant and are not presented herein. However, the presence of the pressure tubes did influence the shock-wave pattern in an interesting way as will be shown.

The photographs of figure 2 show shock-wave patterns which depend on the blowing-rate ratio and whether or not tubes were installed in the model. When air was injected into the shock layer at blowing-rate ratios up to 0.45, the shock thickness for the model with internal tubing, model 1(a), was approximately the same as the shock thickness for the model without internal tubing, model 1(b). However, at higher blowing-rate ratios, exemplified by 0.69 and 1.14, the shock layer of model 1(b) was found to be unsteady and substantially thicker than that of model 1(a). At the blowing-rate ratio of 1.14, supersonic gas injection was indicated by the presence of a secondary shock within the shock layer for both models 1(a) and 1(b). Variations in the secondary shock patterns suggested a variation in the distribution of injected gas over the faces of the models. The secondary shock of model 1(a), except for local irregularities, was located at a uniform distance from the model and suggested a uniform distribution of the injected flow. The secondary shock of model 1(b) has a nonuniform standoff distance with a maximum value near the axis of symmetry, indicating that the injected flow tended to form a jet. A previous report on a similar investigation (ref. 3), utilizing unscreened forward-facing jets, also noted that unsteady flow occurred at certain injected flow-rate conditions.

The question arises as to how well the gaseous injection simulates ablation for the high blowing rates for which unsteady flow occurs. It is expected that in the case of actual ablation produced by radiative and convective heating, the ablative flow distribution would be nearly uniform and steady, particularly for bodies as blunt as those of the present investigation. Thus, the test results with injected air at high flow-rate ratios for model 1(b) are not felt to be a reliable simulation of ablation.

The question of the existence of an interface in the shock layer which separates the injected gas from the oncoming air stream was examined and will be discussed next. The presence of an interface between the injected gas and the shock-layer air is assumed in the theories of references 1 and 2 for predicting the effect of the injected gas flow on the shock-layer thickness. When helium and Freon were injected into the shock layer; a well-defined interface was observed in the photographs obtained during tests at a Mach number of 5 (figs. 3 and 4). The helium-air and Freon-air interface were fairly uniform for a normalized blowing ratio of $\sqrt{1/k} (\rho V / \rho_\infty V_\infty)$ of up to 0.58 for model 1(b) and up to 1.05 for model 2. In the tests at a Mach number of 3, however, when air was injected into the shock layer, the interface was difficult to detect. This was an expected result as the density difference between the two regions was small for these conditions.

An interesting result was obtained when the experimental bow shock-wave position was utilized, together with the method of reference 4, to predict the theoretical solid body necessary to produce the shock. In the method it was assumed that the sonic point on the interface was located one model radius from the axis of symmetry, and that the shock and interface surfaces were spherical. With these assumptions, the shock prediction charts of reference 4 are applicable. The results of the calculations are indicated by the dashed lines at the lower blowing-rate ratios in figures 3 and 4. The congruency of the dashed lines and the actual interface indicates that the bow shock-wave forms as though the interface were a solid body.

The suitability of the normalized blowing-rate ratio for correlating shock standoff distances with gases of various molecular weights injected into the shock layer can be seen in figure 3 where the standoff distances are nearly equal for equal blowing-rate ratios; for example, at blowing-rate ratios of 0.36 and 0.58 the shock-layer thickness of helium and Freon were about equal, although the actual mass-flow rate of Freon was about 5-1/2 times greater than that of helium.

The effect on the center-line shock-layer thickness produced by blowing various gases into the shock layer for all four models at Mach numbers of 3 and 5 is summarized in figure 6. The results are shown as a function of the blowing parameter $\sqrt{(\rho_2/\rho_\infty)(1/k)} (\rho V/\rho_\infty V_\infty)$ (a form suggested by the theoretical considerations of refs. 1 and 2). The density-ratio term, ρ_2/ρ_∞ , is included for correlating the effect of free-stream Mach number on shock standoff distance. It can be seen that the shock standoff distance increases approximately linearly with the blowing parameter and that the data correlate except for the previously mentioned unstable data for model 1(b). Also, the shock standoff distance increases less rapidly with increased blowing for the flat-face model than for the models with spherical-segment front faces.

Figure 6 also presents a comparison of measured and predicted standoff distances for the models with spherical-segment front faces. The predicted distances, taken from the theoretical results of reference 2, were found to be in fair agreement with the experimental results. A similar comparison for the flat-face model was not made because of the absence of theoretical results.

CONCLUSIONS

An experimental investigation was conducted of the effect of simulated gaseous ablation on the bow shock of spherical-segment-face and flat-face models. Gaseous ablation was simulated by injecting the gases air, helium, and Freon through the porous front faces of the models into an oncoming air stream for which the free-stream Mach numbers were 3 and 5. Examination of the test results in the form of shadowgraphs supported the following conclusions:

1. At low ratios of injected-gas to free-stream mass flow, a uniform interface existed in the shock layer between the injected gas and the oncoming air stream for helium and Freon. The location of the bow shock was predictable by treating the interface as a solid body.
2. In general, the shock-layer thickness increased approximately linearly with the ratio of injected-gas to free-stream mass flow and at a given mass-flow ratio was inversely proportional to the square root of the ratio of the molecular weight of the injected gas to the molecular weight of the free-stream air.
3. Theoretical values for the effects of injected gas on the center-line shock-layer thickness were in fair accord with experimental results for the

spherical-segment-face models. A similar comparison for the flat-face model was not possible because of the lack of theoretical results.

Ames Research Center

National Aeronautics and Space Administration

Moffett Field, Calif., May 10, 1965

APPENDIX

BLOWING-RATE CALCULATIONS

The injected gas was metered through a calibrated Venturi for which the unit mass-flow rate in $\text{lb/ft}^2 \text{ sec}$ was given by

$$\overline{\rho V} = \frac{c}{A} \sqrt{\frac{p_m \Delta p_m}{T_m}}$$

where $A = \pi d^2/4$ is the frontal area of the model. The constant c (for the particular Venturi used) was 0.0694, 0.1865, and 0.382 for helium, air, and Freon, respectively. The unit mass-flow rate of the tunnel air stream was given by

$$\rho_{\infty} V_{\infty} = \frac{M_{\infty} \rho_t a_t}{\left[1 + \frac{\gamma-1}{2} M_{\infty}^2 \right]^{(\gamma+1)/2 (\gamma-1)}}$$

(The symbols used in the above equations are defined in the notation section.)

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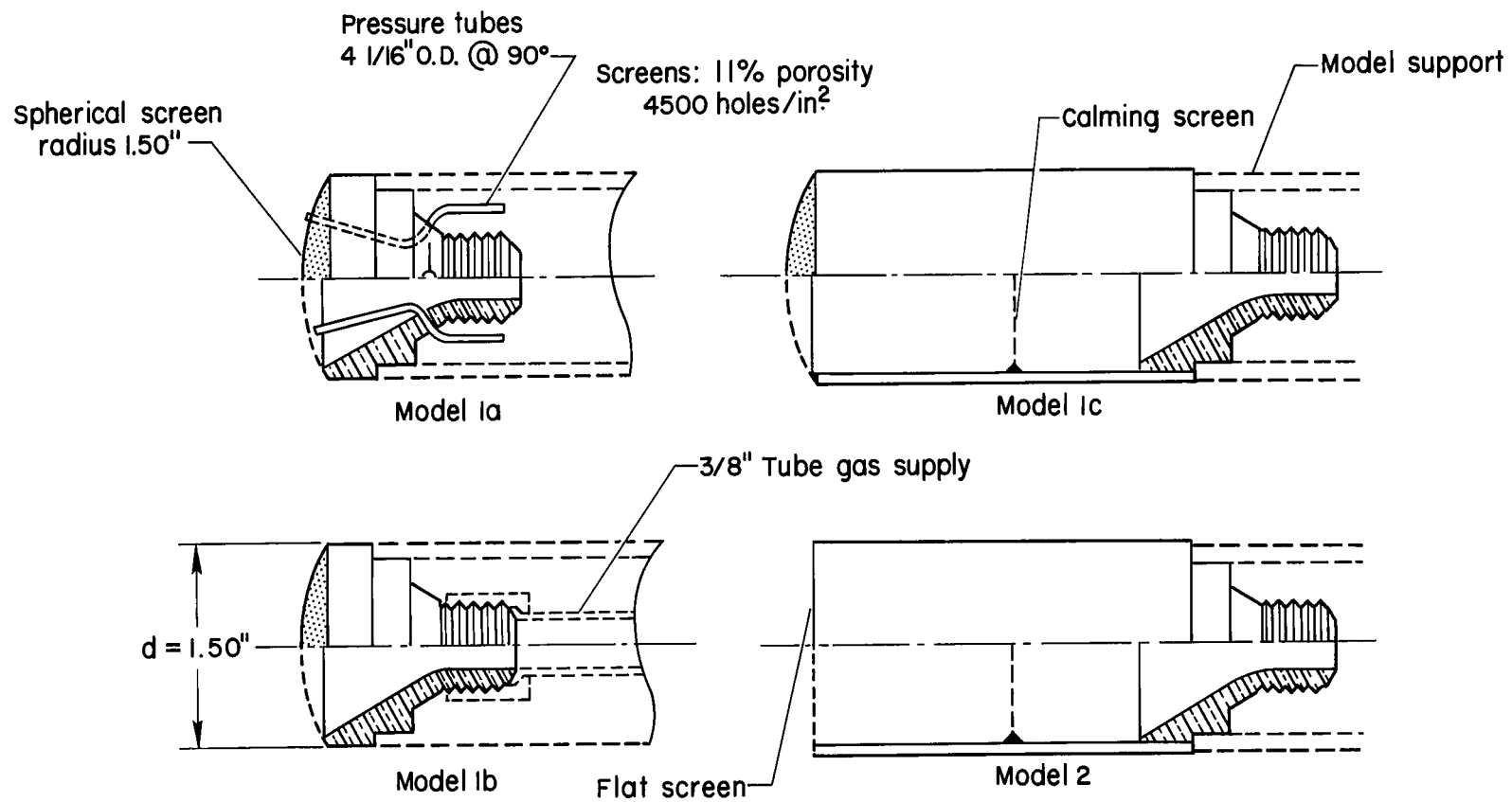


Figure 1.- Model geometry.

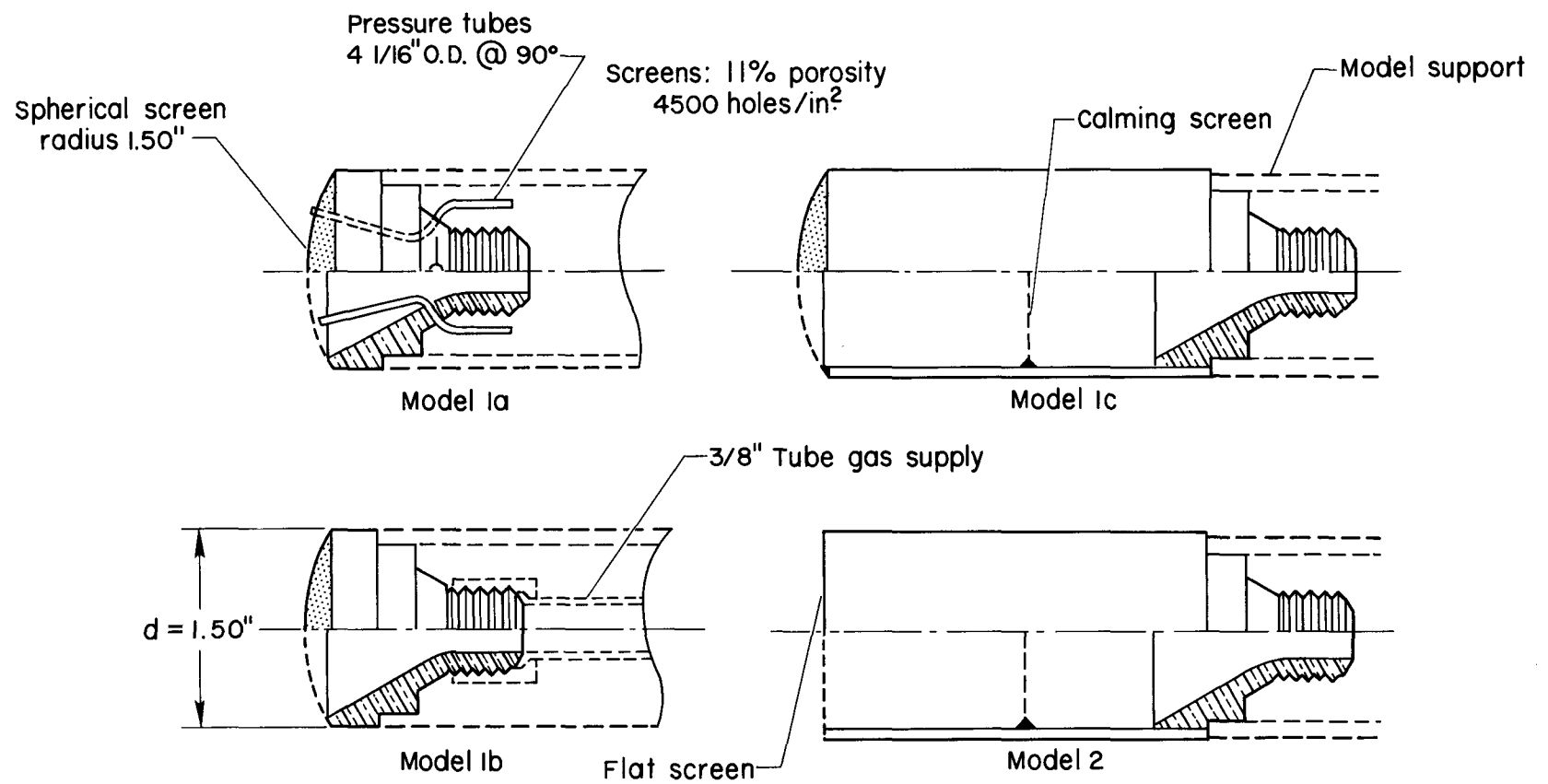


Figure 1.- Model geometry.

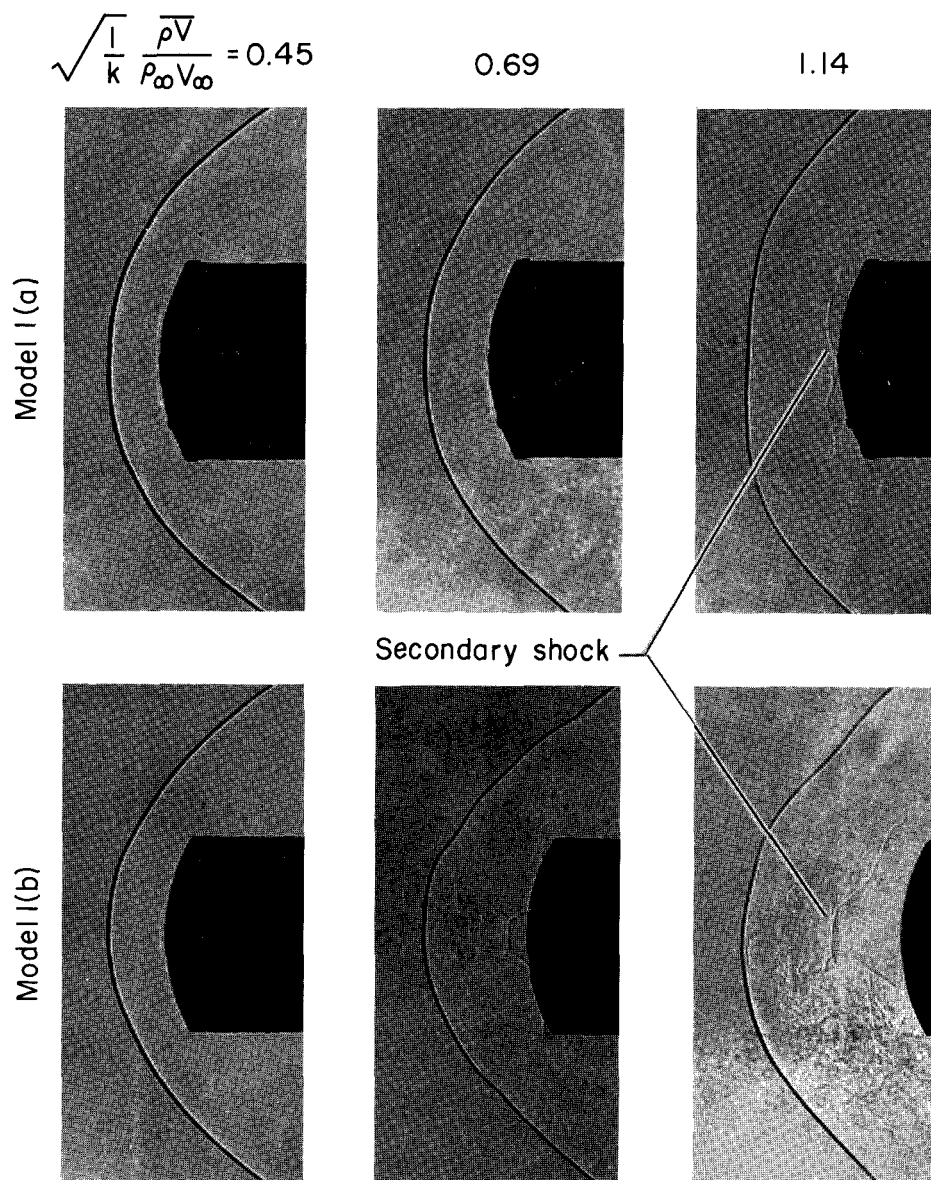


Figure 2.- Shadowgraph photographs of model 1 and bow shock; air injection, $M_{\infty} = 5$.

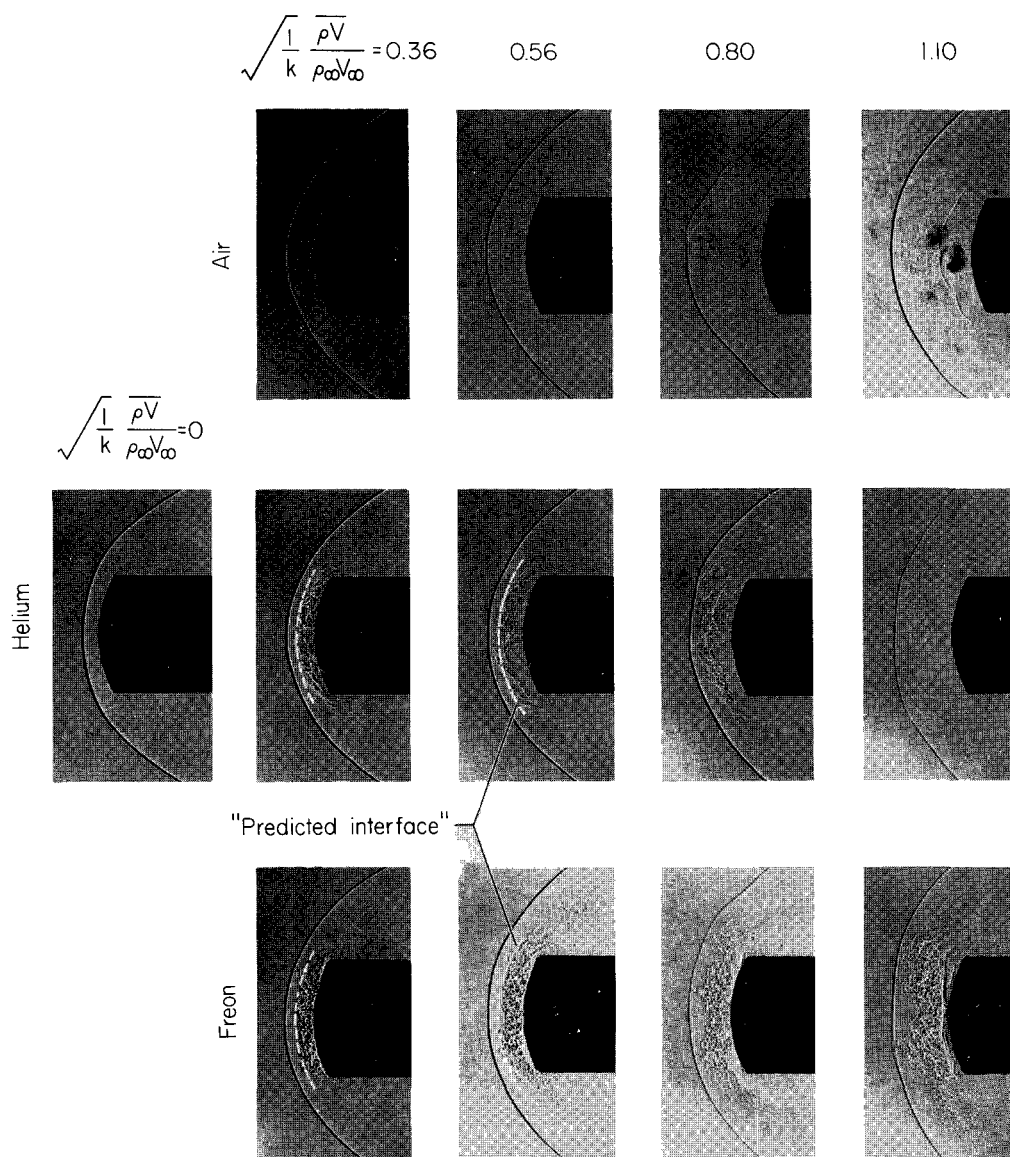


Figure 3.- Shadowgraph photographs of model 1(b) and bow shock; air, helium, and Freon injection; $M_{\infty} = 5$.

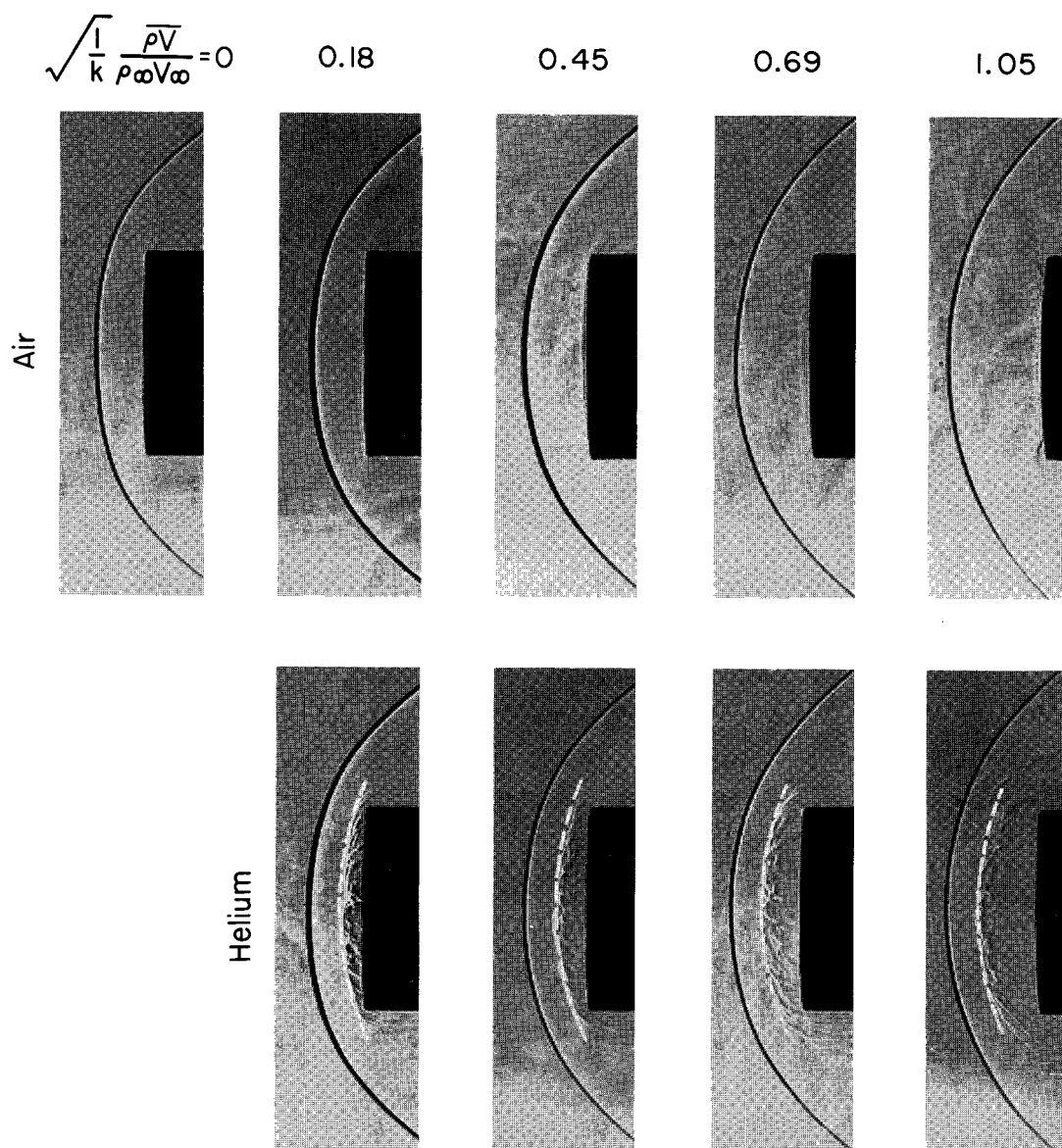


Figure 4.- Shadowgraph photographs of model 2 and bow shock; air and helium injection, $M_{\infty} = 5$.

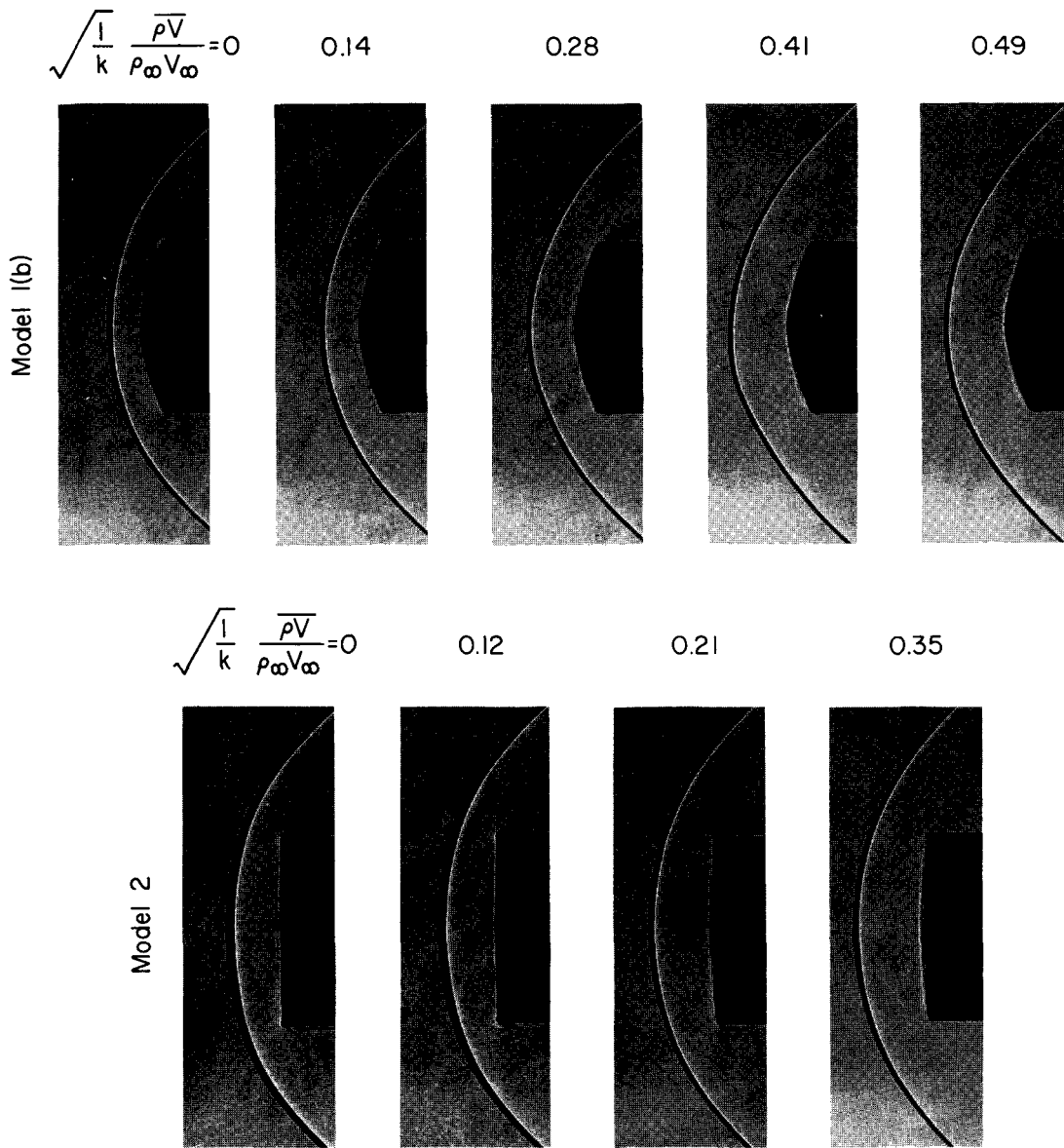


Figure 5.- Shadowgraph photographs of models 1(b) and 2 and bow shock; air injection, $M_{\infty} = 3$.

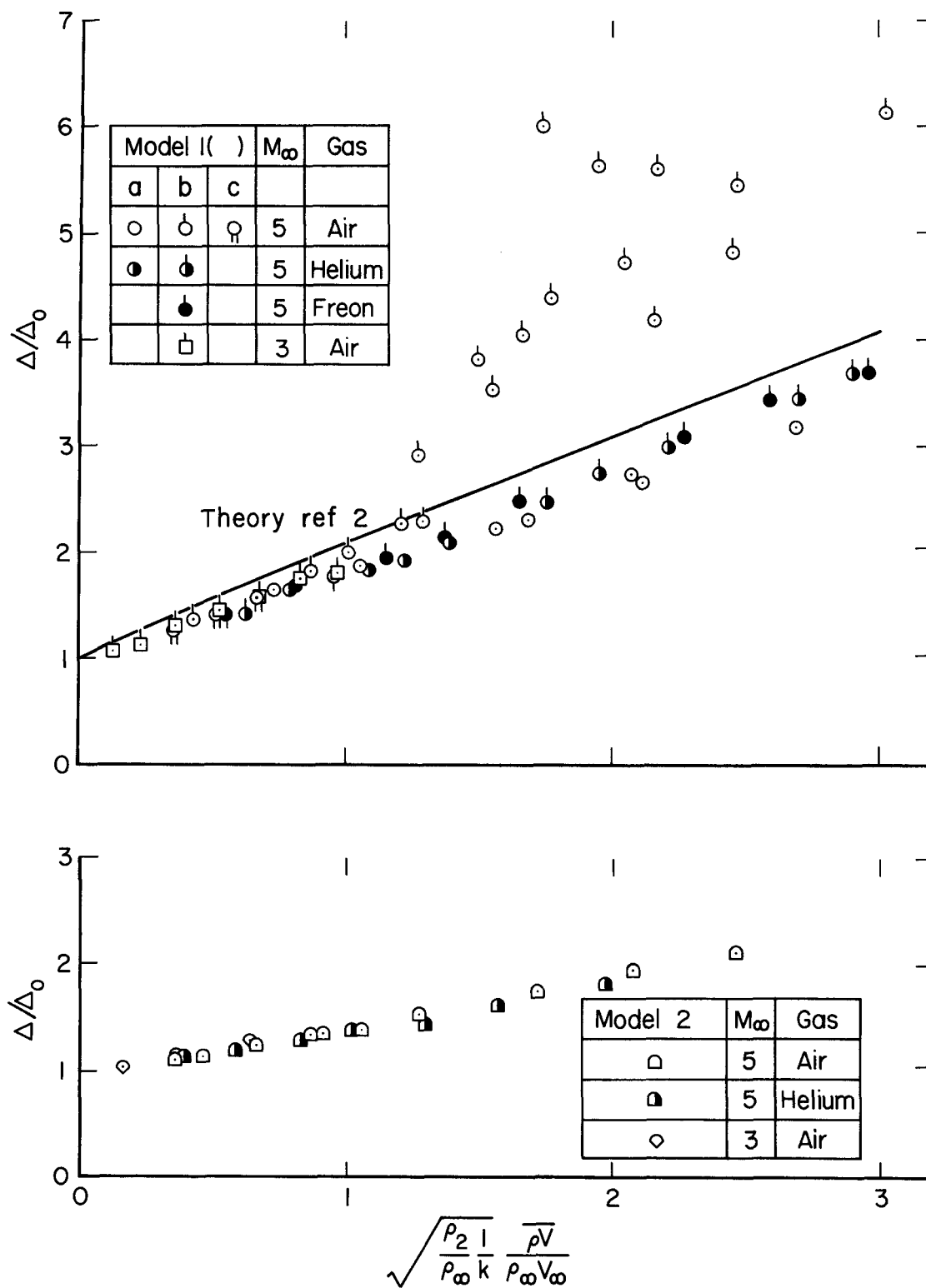


Figure 6.- Correlation of shock standoff distance with blowing-rate parameter.

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